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PRELIMINARY ANALYSIS OF ACCELERATED SPACE FLIGHT IONIZING RADIATION TESTING

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Preliminary Analysis of Accelerated Space Flight Ionizing Radiation Testing

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SUMMARY

A preliminary analysis has been made showing that radiation dose equivalent to 30 years in the geosynchronous environment can be accumulated in a typical composite material exposed to space for 2 years or less on-board a spacecraft orbiting from perigee of 300 km out to the peak of the inner electron belt (≈ 2750 km). Future work to determine spacecraft orbits better tailored to materials accelerated testing is indicated.

It has been predicted that a range of 10^9 to 10^{10} rads would be accumulated in 3-6 mil thick epoxy/graphite exposed by a test spacecraft orbiting in the inner electron belt. This dose is equivalent to the accumulated dose that this material would be expected to have after 30 years in a geosynchronous orbit. It is anticipated that material specimens would be brought back to Earth after 2 years in the radiation environment. The spacecraft would first return to low-Earth orbit for retrieval by the Shuttle/Orbiter and then return to Kennedy Space Center. The space radiation effects on materials could then be analyzed by laboratory methods for the first time.

INTRODUCTION

The material properties of organic polymers as the binder of graphite fiber composites are well recognized and are projected to play an important role in future construction of space facilities. Despite the enthusiasm for these materials, questions remain regarding their long-term stability in the space environment for some applications (ref. 1). It is clear that some form of material studies and testing is required before commitment of these materials in some specific space applications. Unlike crystalline materials, polymers are sensitive to rearrangement of specific chemical bonds and nuclear displacement plays a minor role. This sensitivity to chemical bonding makes the damage threshold for polymers quite low in comparison, and the damage usually shows no characteristic healing as observed for crystalline materials. In addition, the damage rate in polymers is (generally) a nonlinear function of exposure rate since various recombination rates are usually important. Closely related to nonlinear exposure rate effects are particle type effects. Although the electron-to-proton exposure ratio for geosynchronous and low altitudes is somewhat different, the dose in the bulk of the material is largely due to energetic electrons while surface dose is mainly low-energy proton. Therefore, integrated exposure should be a meaningful quantity to simulate for space flight testing.

The objective of this analysis is to match the integrated exposure of a typical composite material in the geosynchronous orbit to some lower Earth orbit; thus, neglecting rate effects. The lower Earth orbits are desirable to enable reasonable accelerated testing of materials in actual space environment. This analytical study also is intended to provide useful information for tradeoff studies for a Shuttle-launched spacecraft that would serve as a test vehicle taking experiments into the charged particle environment and back to the Shuttle orbit for retrieval and return of these experiments to ground laboratories for detailed evaluation by sensitive laboratory analytical equipment.

This preliminary assessment has been limited to AE2, AP5, and AP6 environmental models (ref. 2), which were used in lieu of more recent, more accurate, data which thus far have not been readily available. Therefore, a repeat of this analysis with the more recent data must be made prior to future planning for space flight test design. It is expected that the more accurate environmental data will be forthcoming to enable up-to-date evaluation of spacecraft orbits; however, the general approach of space testing in the inner electron belt is demonstrated herein. Comparison (ref. 3) of the AE2 model environment to the more recent AE5 model indicates that even higher acceleration rates are achievable than those indicated herein.

CALCULATIONAL METHODS

The average stopping power and penetration depth depend on the characteristics of the graphite fibers and epoxy and the blend in which they are incorporated into the composite material. The range of density of the graphite fibers (ref. 4), density of the tetraglycidyl 4,4'-diamino diphenyl methane cured with diamino diphenyl sulfone (epoxy) is shown in Table I, along with the 70-percent graphite and 30-percent epoxy by volume composite mixture density range.

Particulate penetration into a material increases with increasing energy as shown in figure 1 as derived from references 5 and 6. The energy absorbed by a material at a depth x due to incident radiation with fluence spectrum $\phi(E)$ is

$$D(x) = \int_0^\infty \xi(E,x)\ \phi(E)\ dE \tag{1}$$

where the energy deposition coefficient $\xi(E,x)$ for normal incident particles on a sheet of material is shown in figures 2 and 3. Other geometries can be approximated by the methods described in reference 7. The most exposed geometry for depth x is at the center of a sphere of radius x while the least exposed geometry is isotropic incidence on a semi-infinite material slab. The dose at depth x for the most exposed and least exposed geometries was calculated for the geostationary spectrum establishing the shaded band in figure 4. In addition to geometric uncertainties, the radiation environments at geostationary orbits are known only within a factor of five which is also indicated in figure 4 as the upper and lower limits. Figure 4 is the range of exposure to be matched in low-Earth orbit.

The dose rate as a function of altitude for circular equatorial orbits (shown in figs. 5 and 6 as calculated in ref. 2) is utilized in the present method. The long-term average dose rate for arbitrary orbits can be found by using the averaged exposure for circular orbit data of the time varying altitude and averaging over one revolution (ref. 8). The orbit equations are solved by evaluating the orbital angular momentum and integrating the corresponding force equations. The average dose for the orbit is taken as

$$D(r_a,r_p) = \frac{1}{\tau} \int_0^\tau D[r(t)]\ dt \tag{2}$$

where r_a and r_p are the orbit apogee and perigee, τ is the orbital period, and t is time. Equation (1) is now used to seek orbits which can reasonably simulate the 30-year geosynchronous environment as shown in figure 4 as dose versus depth in graphite epoxy material.

RESULTS

Calculations of dose have been made taking the apogee at the peak of the inner electron radiation zone (approximately 2750 km altitude or 1718 nautical miles) and increasing perigee from Shuttle-accessible altitudes until the orbit becomes circular at the peak of the inner electron belt. The results are shown in figure 7 for several depths in a typical composite graphite epoxy material. Curves are for dose of a unit volume of material at the depth indicated. These dose values may be compared to the corresponding values for dose in this material over a period of 30 years at geostationary orbit as shown in figure 4. Note, for example, that the dose in 3-6 mil depths of epoxy material is shown in figure 4 to be in the range of 10^9 to 10^{10} rads. This same dose can be accumulated in 2 years in an elliptical equatorial orbit of 300 km perigee by 2750 km apogee as indicated in figure 7.

In regard to proton radiation, the high surface doses cannot be achieved at the peak altitudes of the inner electron belt. It would be necessary to increase the apogee out to 10,000 km to sample the low energy proton (zero depth curve) as seen in figure 6.

Time spent orbiting in the inner electron belt can be varied to achieve an equivalent 30-year dose at geosynchronous position by increasing the perigee toward a more circular orbit. For example, if the orbit is circularized at 2750 km, the 10^9 to 10^{10} rads range can be accumulated in 5 months versus the 2 years in orbit mentioned earlier. Another important consideration in terms of energy required for orbital plane changes is the variation of exposure rate as a function of orbit inclination. To illustrate how inclination affects the integrated flux over a period of time, consider figure 8 which shows flux contour maps over the altitude and latitude plane (ref. 9). The dotted line shows the trajectory of an elliptical orbit at 0° inclination over which exposure is accumulated. The trajectory of the same ellipse inclined to 30° is shown as the solid line. Note the peak inner zone electrons would be missed entirely by the inclined orbit. Required exposure in orbit for a 28.5-degree inclined orbit would have to be about three times longer than an equatorial orbit for the same accumulated dose. Trade-offs between time of exposure and orbital inclination need to be done using the more recent radiation model. Energy trade-offs in terms of delta velocity for plane changes will be very sensitive in the region of 28.5 degrees to 20 degrees and must be done with the updated values of the radiation model.

As a prelude to design tradeoff studies, the 2-year dose for various unit depths of graphite/epoxy material is shown in figure 9 as a function of apogee for equatorial orbits with the perigee fixed at 300 km. These curves show peak dose near an apogee of 3200 km. Further extension in apogee only reduces the dose for most depths except the surface. To achieve maximum surface dose requires an increase in apogee to 10,000 km.

These preliminary results demonstrate the feasibility of space flight radiation testing under reasonable accelerated rates to achieve simulated 30-year dose at the geosynchronous position. Further studies of time,

orbit parameters, and propulsion delta velocity are indicated. A final analysis using more recent environmental data is desirable at which time further mission design considerations should be made. The possibility of reductions in simulated mission design requirements are indicated by the more intense radiation levels of recent environmental models of the inner electron zone.

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Table I - Density of graphite fibers, epoxy and composite material.

	Graphite Fibers	Epoxy	70/30 Composite
density (g/cm^3)	1.6 - 1.9	1.32	1.5 - 1.7

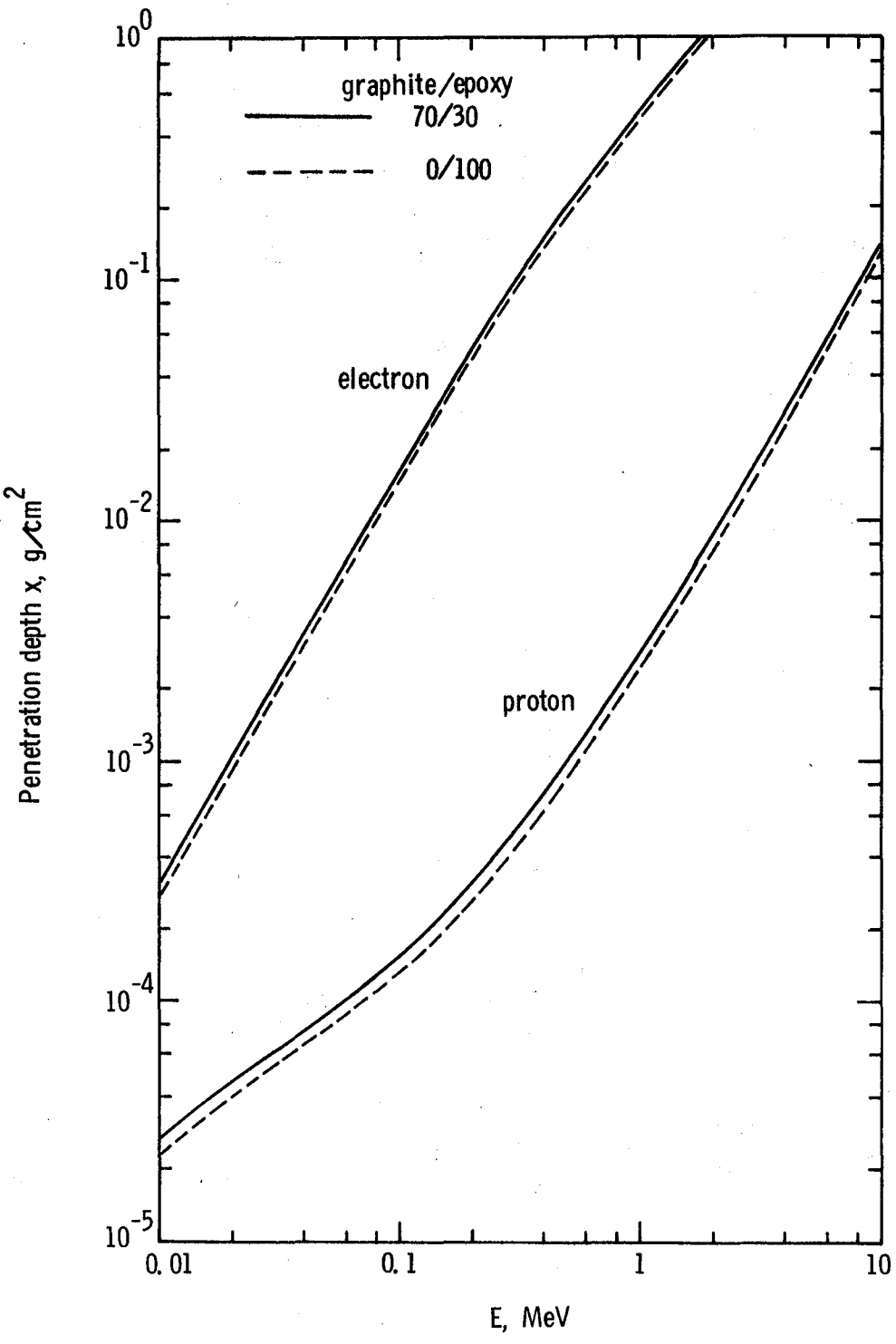


Fig. 1 - Penetration depth as a function of energy for electrons and protons in graphite epoxy composite and pure epoxy materials.

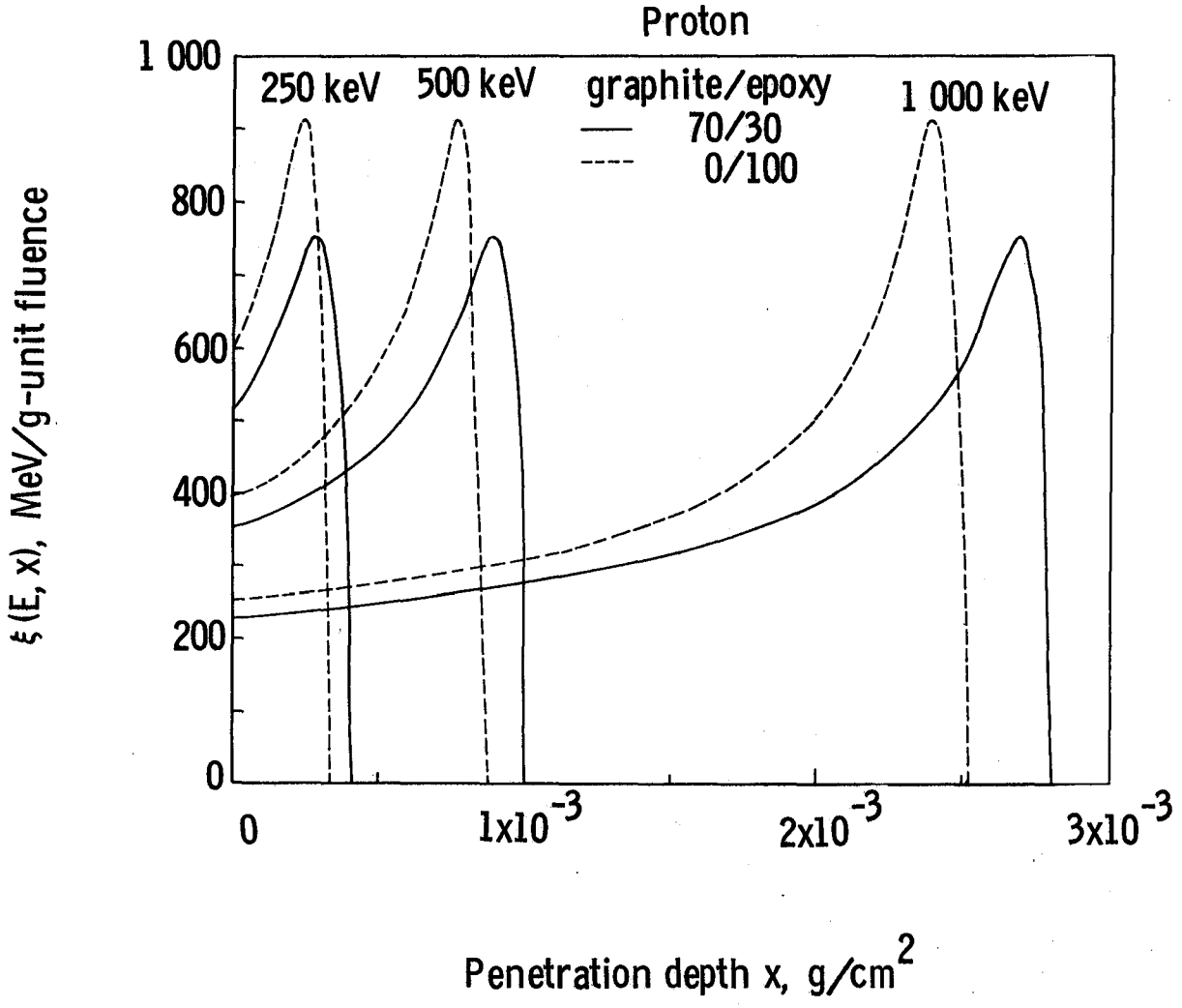


Fig. 2 - Proton energy deposition coefficient for graphite epoxy composite and pure epoxy material.

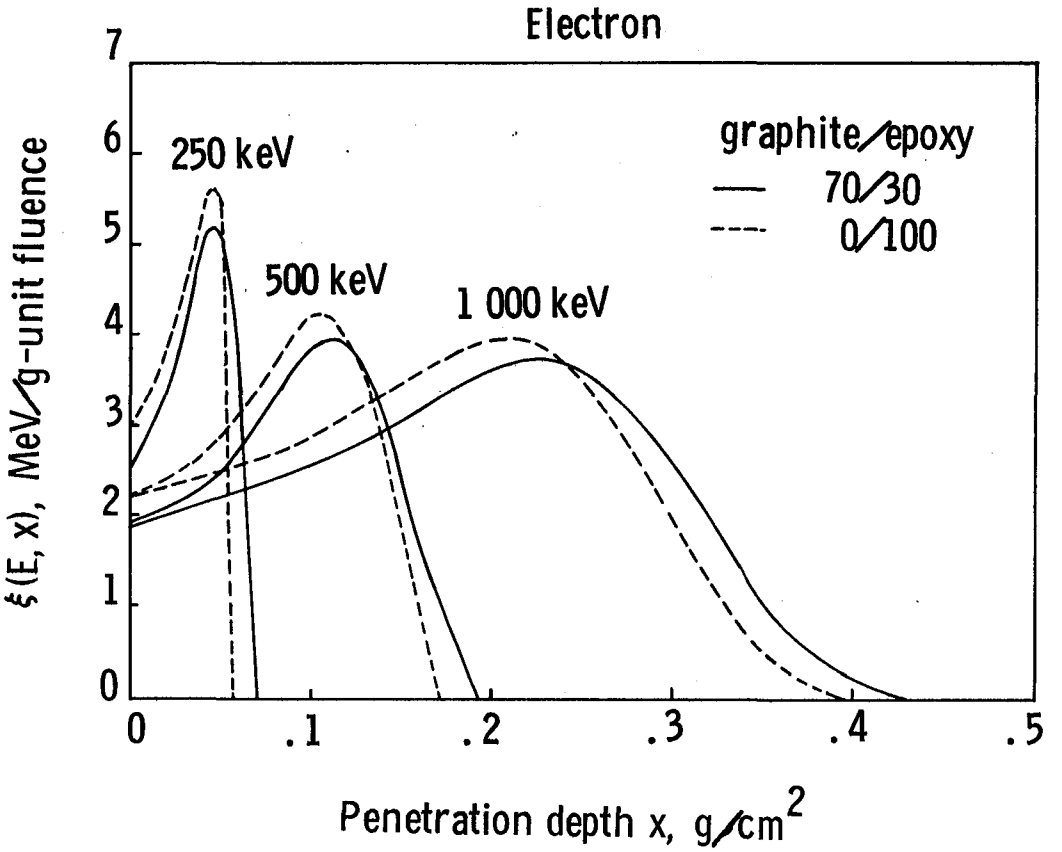


Fig. 3 - Electron energy deposition coefficient for graphite epoxy composite and pure epoxy material.

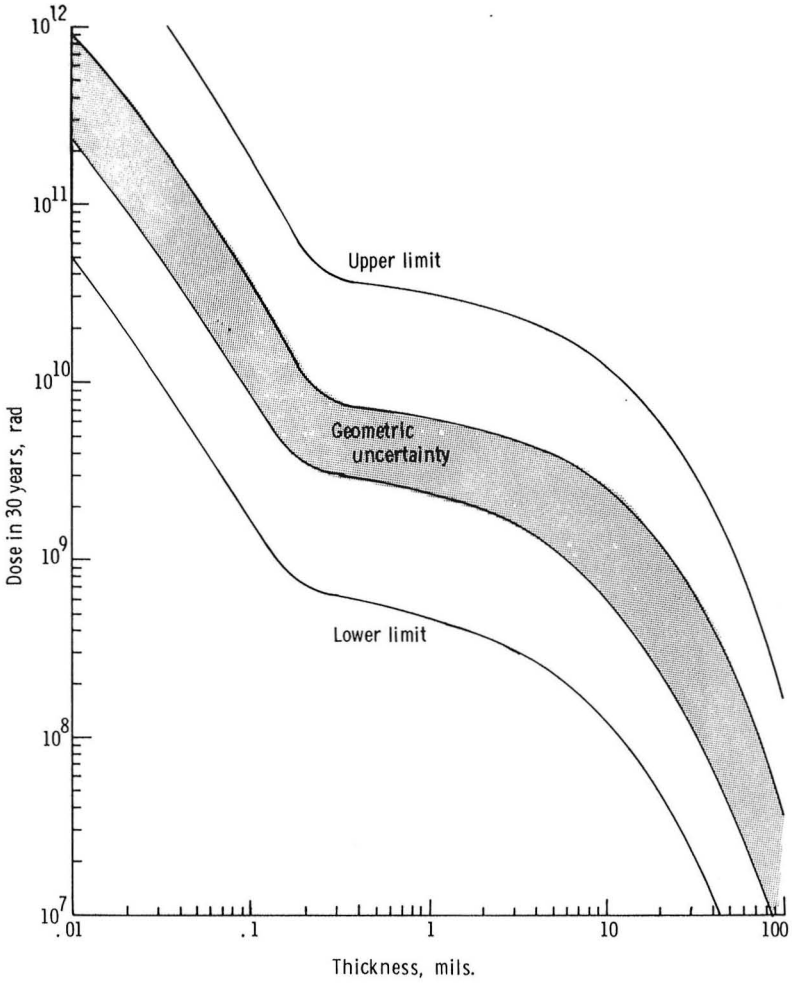


Fig. 4 - Dose in graphite epoxy composite material exposed in geostationary orbit for 30 years.

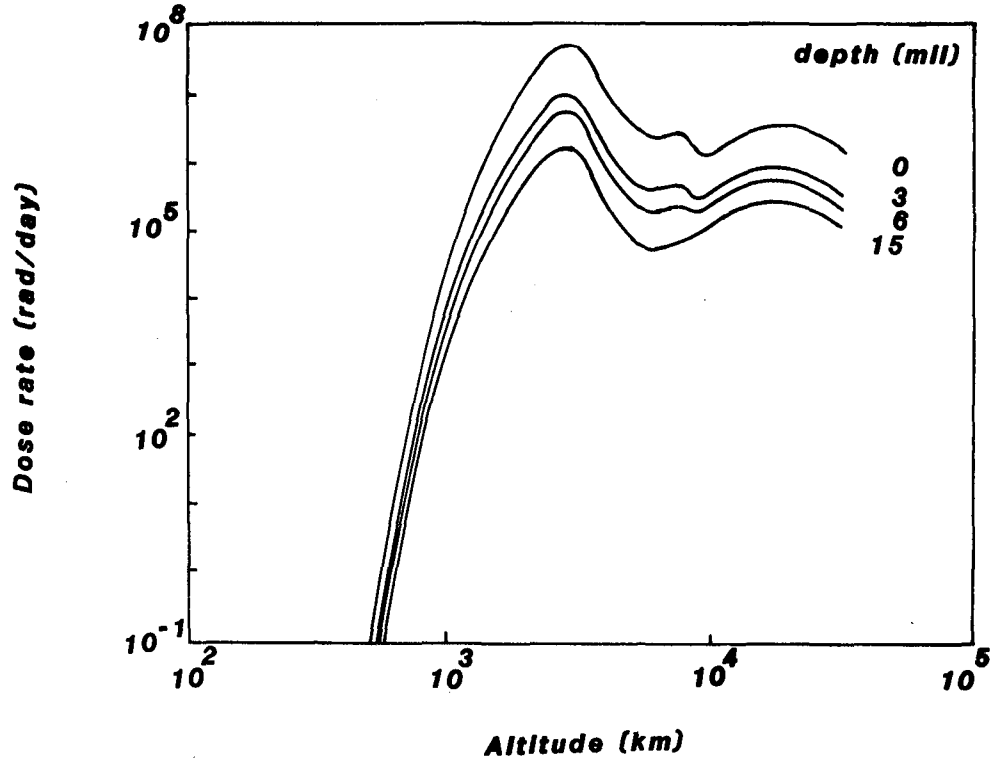


Fig. 5 - Electron dose rate in graphite epoxy composite material exposed in circular orbits at zero inclination.

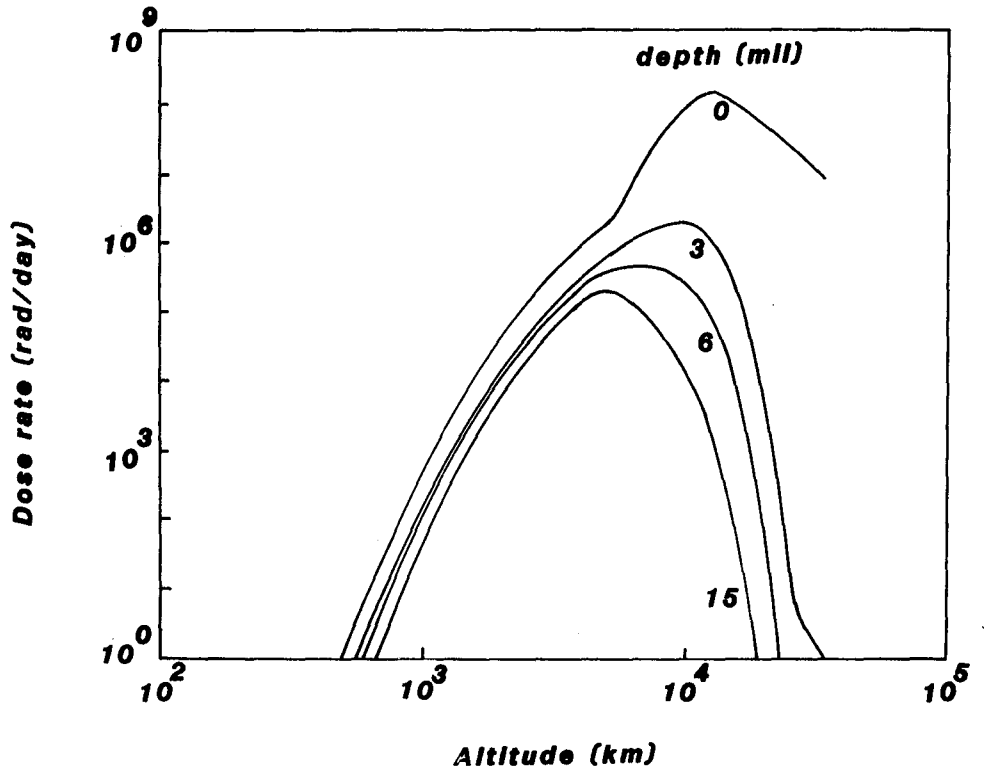


Fig. 6 - Proton dose rate in graphite epoxy composite material exposed in circular orbits at zero inclination.

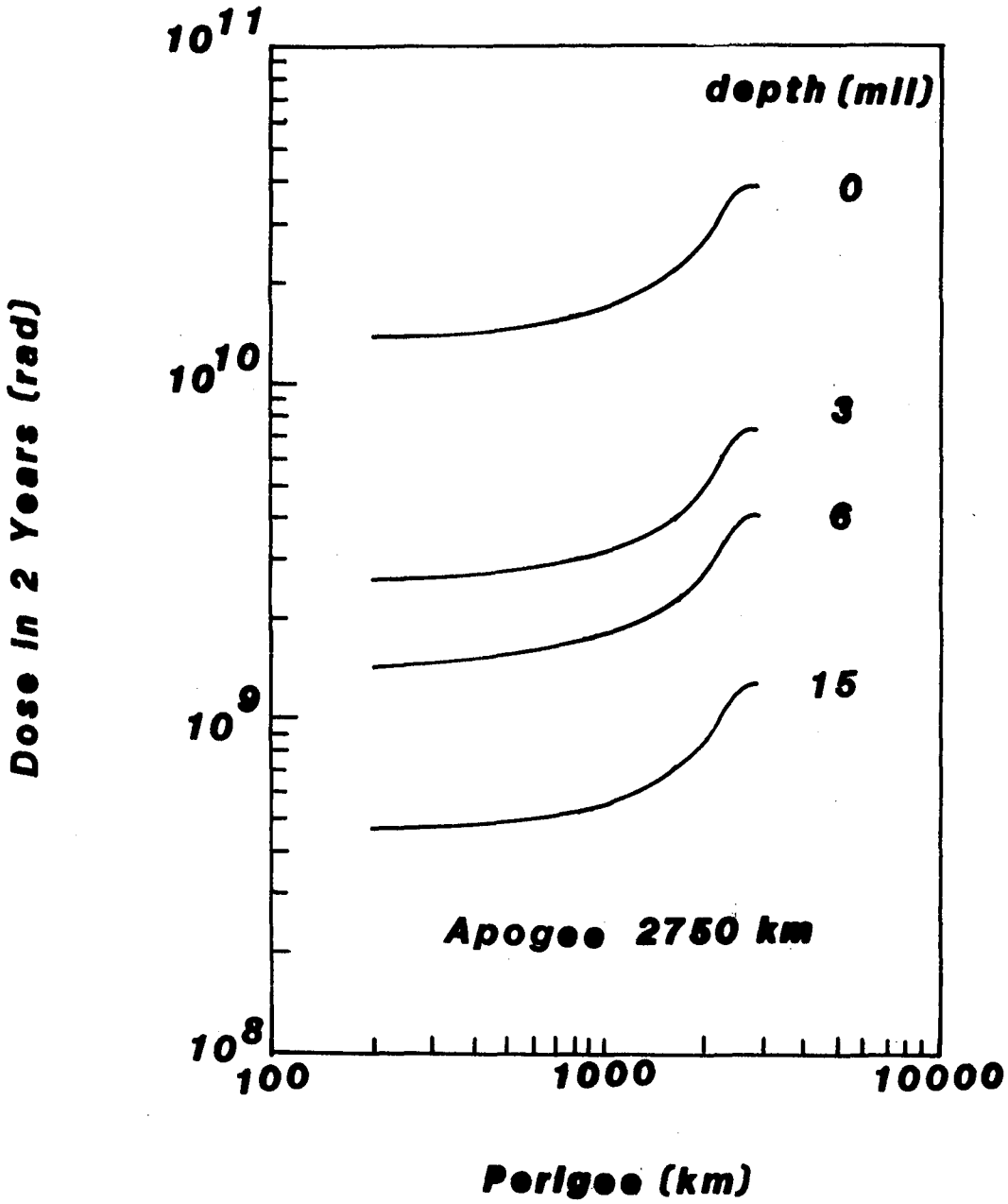


Fig. 7 - Dose in graphite epoxy composite material exposed in elliptical orbits at zero inclination for 2 years.

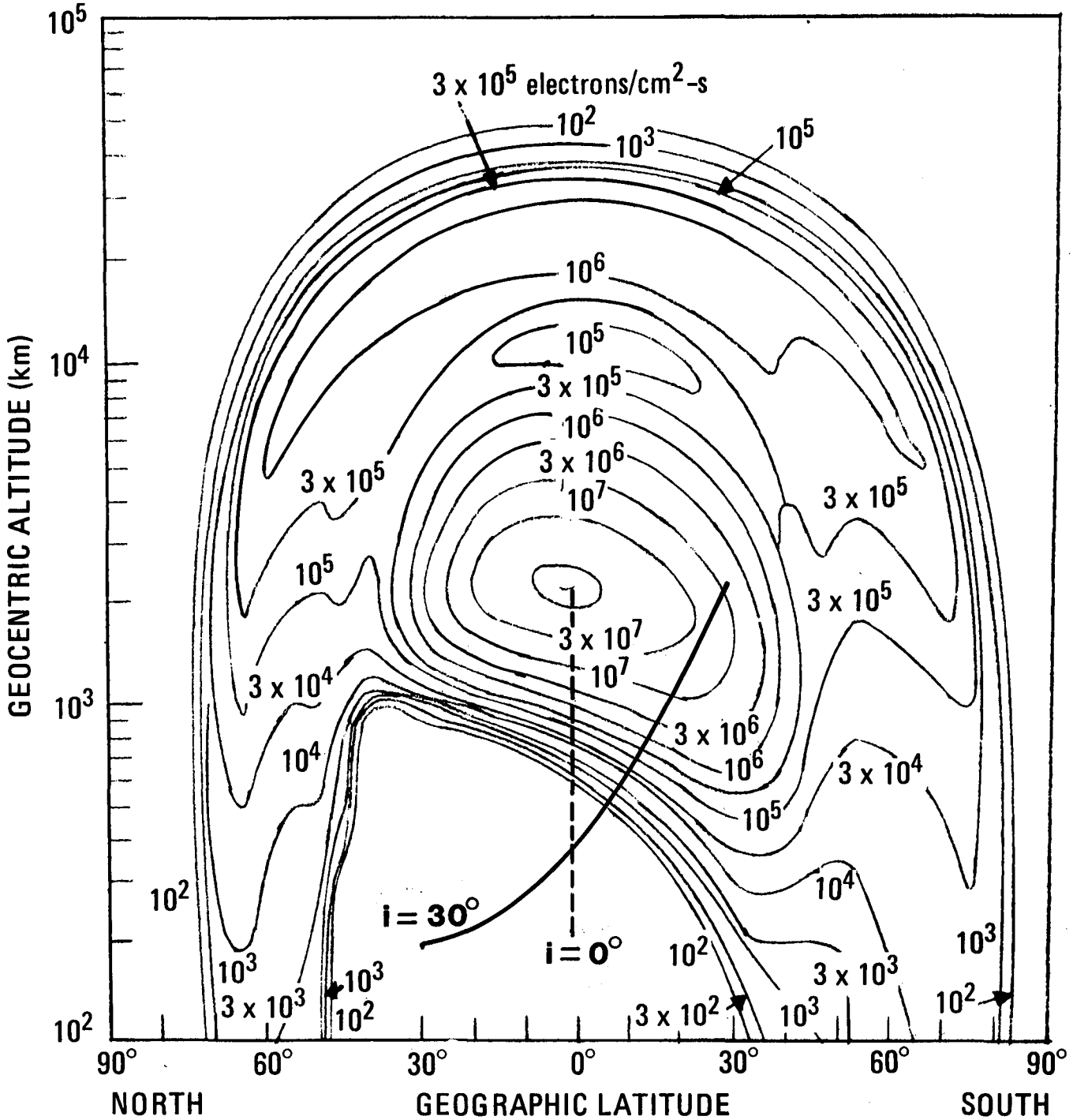


Fig. 8 - Electron flux contours for the Earth's trapped radiation belts.

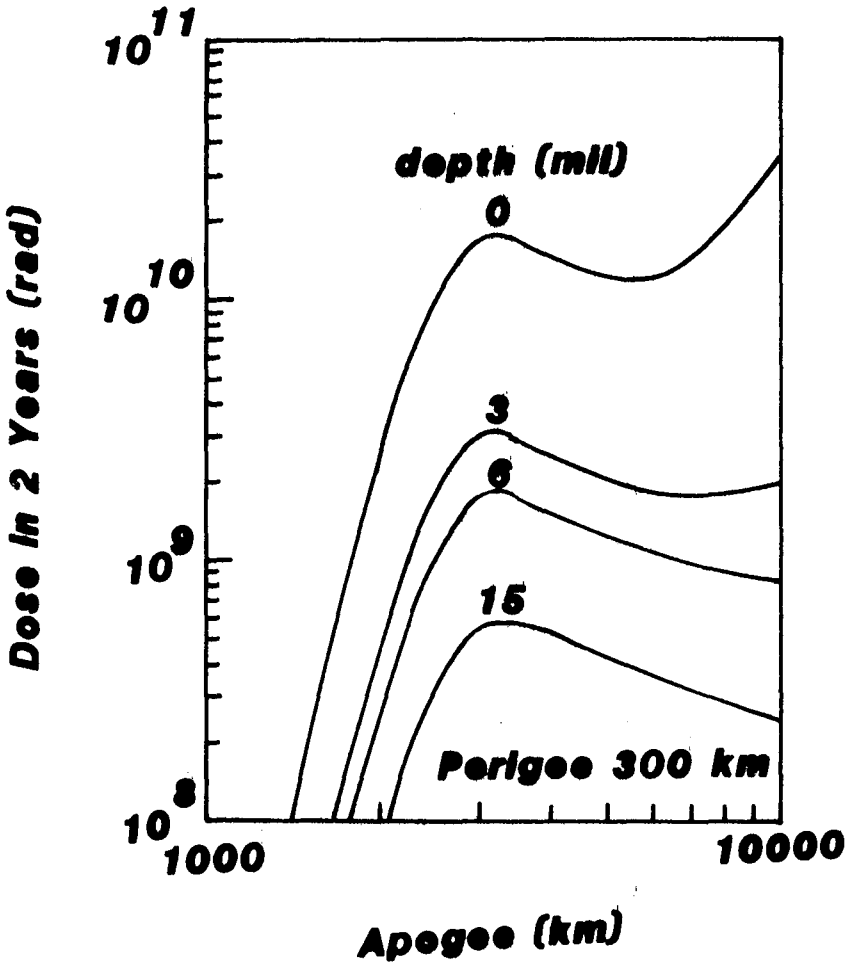


Fig. 9 - Dose in graphite epoxy composite material exposed in elliptical orbits at zero inclination for 2 years.

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15. Supplementary Notes

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16. Abstract

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